First results at SPIRAL-GANIL

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PACS codes: 29, 07, 2920H, 2925C, 2921, 2925G

Keywords: Radioactive Nuclear Beams, ISOL, Cyclotron, Target-Ion-Source

Abstract

The first accelerated exotic beam of the SPIRAL (“Production System of Radioactive Ion and Acceleration On-Line”) facility at GANIL, Caen has been delivered for the first experiment in the end of September 2001. The ^{18}Ne (half-live of 1.67s) isotope has been produced through the projectile fragmentation of a ^{20}Ne primary beam at 95A MeV on a carbon target, located at the new underground production cave of SPIRAL. For this first experiment, a maximum primary beam intensity of 0.18 pμA was used, in order to limit the irradiation of the production ensemble. The radioactive atoms released from the carbon target - heated at 1800°C - were ionised by the compact and totally permanent magnet Nanogan-3 ECR ion source to the charge state 4+. The beam was accelerated by the new compact cyclotron CIME (Cyclotron for Medium Energy Ions) up to the energy of 7A MeV. The maximum beam intensity of ^{18}Ne achieved during this first run was of 2 x 10^6 particles per second at the experimental area. The beam was contaminated by 15% of ^{18}O and a very small amount (<1%) of ^{18}F. The beam was finally purified from the contaminants by a stripping foil placed in the entrance of the LISE spectrometer.

1. Introduction.

The use of high-energy fragmentation for exploring the structure of nuclei far from stability has become one of the major activities at GANIL (Grand Accélérateur National d'Ions Lourds), the first operational high intensity heavy ion accelerator in the 50-100 MeV/nucleon domain. It turns out from the principle of production and separation using a spectrograph – the so-called in-flight method [1]– that the optimum efficiency of the process is reached when the radioactive beam has a velocity similar to that of the primary beam. This production process, however, does imply losses in intensity and/or quality of the secondary beam, which become increasingly important as the beam is slowed down. The ISOL (Isotopic Separation On-Line) method, used at SPIRAL [2] (Système de Production d'Ions Radioactifs avec Accélération en Ligne) since November 2001, provides an alternative for the production and separation of radioactive ion beams, with subsequent acceleration by a K=265 cyclotron (CIME – Cyclotron d'Ions à Moyenne Energie) between 1.7A and 25A MeV, thus opening up the study of nuclear reactions around the Coulomb barrier to radioactive ion beams at GANIL.

In brief, the general scheme of the SPIRAL project is the following: the series of the three GANIL cyclotrons is used as a driver which bombards a production target placed in a heavily shielded cave located beneath ground level in the accelerator building (figure 1). The exotic nuclei produced by nuclear reactions are released from the high temperature target (2000°C), then pass through a transfer tube into an ECRIS source where they are ionised up to a charge-to-mass ratio larger than 1/10. After extraction from the ECRIS with an acceleration voltage up to 36 kV, the low-energy beam is selected by a relatively low-resolution separator ($\Delta m/m = 4\mathrm{x}10^{-3}$) and injected into CIME.

The exotic beams can be accelerated in an energy range of 1.7 to 25 MeV/n and, after extraction, can be selected by choosing the proper magnetic rigidity of the modified alpha spectrometer and finally directed to one of the existing experimental caves. The mass separation is performed for the most part by the cyclotron itself having a resolving power of more than 2,500. An additional separation can be achieved by stripping at the object point of the alpha spectrometer in order to select ions having the same charge-to-mass ratio but different masses, or by using a degrader to select the isobars. However, an intensity loss is the price to be paid for either of these two methods.

2. Target ion source.

In the classic ISOL technique a proton or a light-ion beam is accelerated to a high energy and bombards a thick target, producing radioactive nuclei by spallation reactions, fragmentation of the target and/or induced fission. Other reaction mechanisms, however, come into play with heavy ions. In particular, projectile fragmentation is the process of most importance. In most of cases, the fragments are stopped in the target or catcher, which is heated to a high temperature to facilitate the migration of the radioactive atoms to the surface. Usually the target is located at a short distance from the ion source and the radioactive atoms effuse via a transfer tube to the plasma region where they are ionised and then accelerated. As the atoms are ionised and accelerated in a manner identical to that for stable beams, the resulting radioactive beams have good dynamical and optical characteristics when compared with projectile fragmentation, as well as an energy, which may be precisely adjusted. The originality of the GANIL project lies in the use of an extended range of heavy ions, up to the maximum available energies. Such an approach differs from the proton (or light-ion) beam technique in that the projectile rather than the target is varied in order to produce the different radioactive species, thereby allowing the use of the most resilient and efficient production target for most cases.

For SPIRAL, the high-energy beam delivered by the present GANIL cyclotrons interacts with a thick target, where all the reaction products are stopped. The target is thereby heated by the primary beam up to 2200°C. Such a temperature is a challenge for the target construction in terms of reliability and duration. A numerical code has been developed to simulate the temperature distribution inside the target and is described in [3]. It can be shown with this code that convenient temperatures (<2400K) can be achieved with high primary beam powers if the target presents a conical shape (figure 2). In the case of a low power primary beam, extra ohmic heating can be added through the axis of the target to maintain the diffusion of the exotic ion beam.

After production and diffusion, the radioactive atoms effuse to the ion source through a cold transfer tube that makes a chemical selection, as the main part of the non-gaseous elements sticks on the walls of the tube. The atoms then enter into the ECR (Electron Cyclotron Resonance) ion source Nanogan-3 [4] where they are ionised and extracted to form the radioactive ion beam.

The number of radioactive atoms created by this method depends on the primary beam intensity, which has been recently upgraded [5], and on the integrated fragmentation cross section. However the creation rate of nuclei of interest is always low, and the major problem of the method is to be as efficient as possible in order to maintain suitable radioactive ion beam intensity. This means that the system of production of the radioactive ion beam has to take into account all the loss processes that can occur, like sticking on the walls, leaks, chemical reactions, etc. The production time, including diffusion out of the target, effusion, ionisation and confinement, has to be compatible with the life-time of the nuclei of interest.

In order to test the properties of the target ion source systems, the separator SIRa (limited to 400W of primary beam power) was built in 1993. It allowed the test of different configurations of production systems under real conditions [6-9]. The present Nanogan-3 configuration is composed of a graphite target coupled to a 10 GHz permanent-magnet ECR ion source via a cold transfer tube. This configuration is mainly dedicated to gaseous elements that do not stick on the walls.

The release efficiency from the target depends on the temperature and on the grain size of the carbon. Figure 3 shows the dependence of this release efficiency with the temperature and the grain size, explaining the choice of the 1 μm grain size for the carbon micro-structure.

Particularly for ^{6}He and ^{8}He, a new target has been developed which is divided into two parts because of the long range of He in carbon. The first part, the production target, induces fragmentation of the carbon primary beam and also fragmentation of carbon atoms of the target. Helium produced by projectile fragmentation stops in the second part of the target (the diffusion target) while the He produced by target fragmentation stops in the production target. The carbon ions of the primary beam that do not react are also stopped in this first part. By this means, the production target is heated by the primary beam power, allowing the diffusion of the He atoms produced by the fragmentation of the carbon atoms of the target, while the diffusion target needs ohmic heating to reach a suitable temperature for diffusion.

Radioactive oxygen beams have been produced by using the fact that a radioactive oxygen atom produced in the graphite target can combine with the carbon and produce a CO molecule that diffuses to the ion source.

The intensities of all possible beams available at SPIRAL are permanently updated in the GANIL web-page www.ganil.fr. In all cases, off-line reliability tests have been successfully performed over a long period (more than 20 full days). On-line tests show that the targets can work for at least 15 days without damage.

The behaviour of the ion source has also been studied by comparing the charge state distribution of multi-charged ions during different moments of the production. Figure 4 shows that after a short delay of out-gassing, the source behaviour is no longer affected by the presence of the target in its neighbourhood. As expected, the charge state distribution of radioactive noble gases does not show any difference from that of stable isotopes.

Radiation risks, choice of materials and the reliability of the radioactive ion beam production system have been taken into account in the design of the production cave.

2.1. Radiation levels around the target ion source system.

During interaction of the primary beam with the target, a large amount of energetic particles, and particularly neutrons, are produced. These high velocity neutrons have a long range in matter and activate the materials along their path. The energy and the density of neutrons depend on the angle with the primary beam axis. The highest energy and density of neutrons are emitted in the direction of the primary beam. For this reason the target has been placed in such a way as to minimize the materials exposed to the neutron flux, and the first magnet of the source is located at an angle greater than 90° to the beam direction.

After irradiation the materials in the cave, which have been activated by neutrons, produce high levels of gamma radiation. This makes manual operation or removal of the source impossible. For this reason a remotely controlled removal system has been built.

Irradiation of some materials, especially polymers, can lead to modifications of mechanical and chemical properties and can thus reduce the reliability of the equipment, which they constitute. Whenever it has been possible metallic materials have replaced the polymers. Ceramic materials and polyurethane that provide strong resistance to radiation [10] have been chosen when the use of metallic material was impossible, such as where electrical insulation is required, for example. For the mechanical part of the design, aluminium is preferred to stainless steel and copper materials because its irradiation by neutrons creates less long-lived radioactive isotopes [11]. This necessitates the use of ethylene-propylene ‘o’-rings on the vacuum chambers.

A system placed in high radiation fields must be reliable. To increase the reliability of our system, we have taken into account the resistance of materials under radiation, their position and their screening, the quick dismounting possibility and the cost. All the elements that were not needed near the target and ion source were located outside of the cave. So the primary mechanical pumps, the valves located on the primary pumping circuit, the gauges, the air distributors for the valves located inside the cave, and all motors, electronics and power supplies have been placed outside the cave. Only the turbo-molecular pumps, cables and the air or water connections are inside the cave, together with the target ion-source. Two turbo-molecular pumps have been installed so that, in case of a breakdown of one of these pumps the other will continue to operate without stopping radioactive ion beam production.

During irradiation, some radioactive gases are produced and pumped by the vacuum system. In order to limit the amount of radioactivity released into the air, the gas ejected by the primary pumps is stored in bottles.

In such systems where a target is activated by primary beams, the risk of dispersion of radioactive elements into the air during disconnection is present. To limit this risk, valves close off the target ion source system and the front ends before any disconnection begun. The volume between the valves is vented and controlled by a dedicated detection system before being disconnected. After disconnection and removal of the target ion source system, the two front ends can be removed for maintenance if needed. In order to minimize the spread of contamination, a double valve was installed at the entrance of the High Energy Front End (HEFE) and at the exit of the Low Energy Front End (LEFE) that permits closing the chambers before removal and transfer to an area specially adapted to handle contaminated objects. The removal operation of the front end needs human intervention. To limit the exposure time of workers in the cave to this operation, all electrical, air and water connections of each front end have been joined together on a quick connector. Quick flange clamps help fast vacuum disconnections.

In the event of a contamination release inside the cave, precautionary measures have been taken such as covering the walls, the ground and the benches with special radio-resistant and non-contaminable epoxy coatings used in nuclear plants, and also installing a nuclear ventilation system.

3. The CIME accelerator.

CIME has been designed according to the exotic ion physics to which it is dedicated. A compact cyclotron solution has been chosen since it offers very good mass separation capabilities for a relatively low cost. To cover the energy range required, a K = 265 has been chosen. The principal points on which CIME differs from a conventional cyclotron are the following:

a) A cross structure made of four return yokes (instead of two in a classical cyclotron) and a common circular pole equipped with four sectors has been chosen for the magnetic design. Despite some initial anxieties that this new structure has aroused, we were convinced that the required manufacturing qualities and mechanical tolerances would be obtained. The sectors were machined with a 0.02 mm precision in parallelism and 0.05 mm on the side profile. The pole (3.5 m in diameter) is of the same precision.

b) The support and alignment are done by twelve hydraulic jacks, allowing fine adjustments (± 0.01 mm) in all three dimensions. After final assembly, the gap precision obtained is better than 0.05 mm over the whole useful area. A maximum gap reduction of 1.2 mm at the centre was measured as a result of the magnetic forces acting on it.

A weak point of large compact cyclotrons is that the vacuum pumping system [12] is situated at the periphery of the vacuum chamber. To insure a transmission of the injected beam without losses by charge-exchange, it is necessary to maintain a pressure of $<10^{-5}$ Pa inside the cyclotron vacuum chamber, mainly at the centre where losses are prohibitive at low energy. We therefore chose to develop a new pumping system of cryogenic panels placed on the pole of the machine in the ejection valley, insuring a pumping speed of 25 x 10^{3} l/s. Results are entirely up to expectation, since the pressure limit reached is 4.8 x 10^{-6} Pa.

The main elements of the CIME accelerating system are the saw-tooth buncher [13, 14] and the cyclotron radio-frequency (RF) system [14]. Both systems were designed and manufactured in close co-operation between GANIL and the RF and mechanical design groups from the IPN-Orsay. They are operated in the bandwidth 9.6 to 14.5 MHz and can stand a 10^{-2} frequency shift under power, to tune the rare beam and to accept dedicated mass measurement experiences. The electrode tip has to be changed to improve the transmission efficiency for different harmonic (h) operations and two sets of them have already been designed and manufactured respectively for h = 2, 3 and h = 4, 5.

A sliding (650 mm displacement) short circuit is used to tune each resonator, while two trimming stubs are used to control thermal drift and the frequency shifts applied for secondary beam tuning. This gives strongly variable shunt impedance and power requirements ranging from 15 to 42 kW, in accordance with the voltage law. The power amplifiers are based on the standard GANIL 100 kW amplifier, but are tuned in such a way that the operating costs are reduced. Variable-anode impedance values were chosen in order to match at each frequency the amplifier maximum output power to the cavity power requirements.

The need of excellent transmission of the injected beam, and qualities (emittance, dispersion in energy, pulse length, mass separation) leaded to the following constraints :

i) the control of the injected beam as close as possible to the entrance magnet;

ii) the matching in 6 dimensions of the beam to the acceptance of the inflector and the cyclotron, which requires a low energy beam line and a buncher;

iii) the bunch transmission up to extraction without loss, by controlling the magnet isochronism and pressure conditions;

iv) an extraction efficiency which depends only on the turn separation and the quality of the lost two turns.

One has therefore divided the CIME operation into 2 parts: The first from 2.7 to 25 MeV/u with a standard MULLER hyperboloid inflector, and the second from 1.7 to 6.3 MeV/u on the harmonic 4 and 5 with another hyperboloid inflector and the same maximum injection voltage [15].

In theory, acceleration conditions should allow to change over automatically and “blindy” from a stable ion beam of measurable intensity to an exotic ion. This is possible with almost no adjustment due largely to the very good reproducibility of the magnetic field, which allows achieving isochronism tuning with a 3 Gauss precision.

4. Accelerating the first beams.

SPIRAL began its test period on April 1998. Prior to the authorisation to produce radioactive beams, 650 hours of stable beam tests were allowed for the commissioning of the machine. The whole working range (figure 5) of the cyclotron CIME was successfully tested with stable beams. This diagram represents the possibilities of the machine in term of energy range from 1.7 to 25 MeV/A. One can see that for a given charge to mass ratio (Q/M) and for a desired beam energy, the harmonic number and the magnetic field can be determined within the machine boundaries. During these tests, major efforts have been done to improve the injection matching conditions in different acceleration configurations and to solve an unexpected off-centring problem. The most remarkable result is the very good transmission for this type of machine (table 1).

Another important feature of accelerating beams using a cyclotron with a large number of turns is that it allows combining the mass selection process and the acceleration, with good efficiency.

If one consider that CIME is tuned for accelerating a given M/Q mass ratio, for another ion, with a different mass-to-charge ratio (M_1/Q_1), the synchronism condition will not be fulfilled, and its relative phase with respect to the RF system will grow during acceleration. The second ion with mass-to-charge ratio (M_1/Q_1) will ends up with a phase relative to the RF greater than 90°, which means that it will no longer be accelerated and will get lost inside the cyclotron (figure 6). This mechanism allows the elimination of any ion if the mass-to-charge ratio is such that its phase exceeds 90° before reaching the extraction radius of the cyclotron. This condition corresponds to first order to:

$$\left[\frac{M_1}{Q_1} - \frac{M}{Q}\right] \Big/ \frac{M}{Q} < \frac{1}{2\pi \; H \, N_{turn}} \tag{1}$$

where N_{turn} is the number of turns and H the harmonics. Hence the mass resolution of a cyclotron is defined as :

$$R = 1/2\pi \; H \; N_{turn} \tag{2}$$

Depending of the harmonic, the mass resolution of CIME can reach 1.6 x 10^{-4}.

As far as the purification of very rare isotope is concerned, the achievement of very good mass resolution is not sufficient, since stable contaminants can dominate the intensity of a given radioactive isotope by several orders of magnitude. The selection achieved in the cyclotron, as a result of the RF acceleration, does not remove all the distribution tails of the unwanted beams.

5. The first on-line beam.

The first accelerated exotic beam of SPIRAL has been delivered for the first experiment in the end of September 2001. The ^{18}Ne (half-live of 1.67s) isotope has been produced through the projectile fragmentation of ^{20}Ne primary beam at 95A MeV on a carbon target. For this first experiment, a maximum primary beam intensity of 0.18 pµA was used, in order to limit the irradiation of the production ensemble. The radioactive atoms released from the carbon target - heated at 1800°C - were ionised by Nanogan-3 ECR ion source to the charge state 4+. The beam was accelerated up to the energy of 7A MeV. The maximum beam intensity of ^{18}Ne achieved during this first run was of 2 x 10^6 particles per second at the experimental area. The beam was contaminated by 15% of ^{18}O and a very small amount (<1%) of ^{18}F (figure 7). The beam was finally purified from the contaminants by a stripping foil placed in the entrance of the LISE spectrometer.

The efficiency of the overall production system can be disentangled in the following way: more than 90% of the produced atoms diffuse out of the target and arrive in the ECR ion source and 15% of these atoms are extracted in the charge state 4+. The transmission of the low energy separator, corresponding to the first half of the injection line of CIME was of the order of 50%, while the transmission of the CIME accelerator including the beam pulsing losses and beam extraction was also 50%. The unexpected losses in the transmission of the separator were due to a misalignment. This problem was solved in great part by including a magnetic steerer in the beam line. The other efficiencies are perfectly compatible with the ones expected. The final RIB intensity reached with this low primary beam intensity corresponds to the one published in the prospective of SPIRAL (see www.ganil.fr/spiral/beams_commissioning.html). The present design of the Carbon target allows increasing the primary beam intensity up to 1 pµA, which would correspond to 10^7 particles per second of ^{18}Ne.

The excellent stability and reproducibility of the whole production and acceleration system of SPIRAL should be pointed out. During the experiment one could easily change the tuning of the cyclotron from ^{18}O – used for calibrations – to ^{18}Ne within around 15 minutes.

The intensity of the radioactive ^{18}F accelerated at the same energy (7A MeV), was measured at the end of the run, just after a small change on the CIME magnetic field. We measured an intensity of 2 x 10^5 particles per second with the same primary beam intensity (i.e. 0.18 pμA). It is expected that, at the maximum intensity and using a primary beam of ^{19}F, the final ^{18}F intensity would be of the order of 10^7 particles per second.

At present, beams of ^8He at 15.4A MeV and 3.5A MeV and ^{76}Kr at 7.3A MeV were also delivered for experiments. The intensities achieved using a primary beam power of respectively 1.4kW and 500W are in perfect agreement with the expected ones. The intensities for ^8He at 15.4A MeV and 3.5A MeV, corresponding to the charge states of 2+ and 1+, were respectively 1.4 x 10^4 pps and 4 x 10^4 pps. For ^{76}Kr, the intensity obtained was 1 x 10^6 pps.

It should be noted that we experimented vacuum leak problems in the zone close to the target during the ^8He runs. Changing the design of the window support has solved this problem.

A new target for He production with the capability to withstand up to the beam power of 3kW (the maximum allowed intensity for ^{13}C as primary beam) will be in operation in the autumn 2002. The maximum operation intensity of 6kW in the production target for Ne, Ar and Kr primary beams should be achieved in 2003.

6. Spectroscopy of ^{19}Na.

Concerning the experiment, the aim was the spectroscopy of the exotic ^{19}Na nucleus. Very little is known about this nucleus, it has a N = 8 magic number (^{19}Na = ^{16}O + 3p), its ground state is proton unbound by Q = - 0.320 MeV and there is an excited state at the energy of 120 keV. The purpose of our experiment was to measure the width, spectroscopic factor, spin and the position of the first excited states in ^{19}Na. It has been also reported interests in nuclear astrophysics for this nucleus, since it can be use as a step in the double proton capture with ^{18}Ne. We will also investigate this striking subject.

The method we have used to investigate this nucleus was the elastic resonance scattering in inverse kinematics using a thick target [17]. In our experiment the ^{18}Ne radioactive beam has been impinged into a 1 mm thick solid hydrogen cryogenic target [16]. This target has shown very good qualities, the homogeneity has been checked by comparing results with the ^{18}O stable beam. The final resolution is better than 40 keV in the center of mass system. In this method, the heavy ions are slowed down in the target and, at the energy of the SPIRAL beam, the particles stop inside the target. If the energy of the particles, at some point along their slowing down trajectory, corresponds to a resonance energy of the compound nucleus (^{19}Na = ^{18}Ne + p), the probability for scattering increases dramatically. After a scattering event the recoiling proton is ejected in the forward laboratory direction, and is subsequently detected by an array of silicon detectors. A thick Si detector has been used in order to cover a larger energy interval. The inverse geometry and small specific energy loss of the protons strikingly reduce the influence of the beam spread on the final resolution. The very thick target makes it possible to obtain a continuous excitation function over a wide energy range without changing the beam energy. We have used a thick E silicon detector for the measurement of the scattered protons. A thin ΔE silicon detector, placed in front of the thick one, has permitted a clear identification of protons from a E-ΔE plot and the rejection of β delayed proton radioactivity events or inelastic processes. From a measurement of the angular distribution one can obtain directly the spin assignment. The E detector is also position sensitive to permit a reconstruction of the trajectory.

The first results are very promising; there are clearly several (more than 5) structures (resonances) in the proton spectrum, with large widths (more than 100 keV), see figure 8. A final report needs a more precise R-matrix analysis. It will be very interesting to compare the results with the excited states of the mirror nucleus ^{19}O. For a first experiment with the SPIRAL facility, it is a brilliant experiment since the ^{19}Na nucleus will become one of the most known nucleus is this region of the nuclear chart.

7. Perspectives.

SPIRAL can deliver beams of noble gas, oxygen, nitrogen and fluorine with optima intensities using the present target and ion source in the energy range of 1.7A to 25A MeV, depending on the Q/A ion ratio. A new very low energy beam line (LIRAT [18]) is being built presently and will allow to deliver multi-charged beams at keV energies. In parallel, new target and ion sources are being developed in order integrate other elements in the "menu" of SPIRAL beams, like alkali (see MONOLITHE source in ref. [9]).

Beam time of SPIRAL is presently estimated to be of the order of 2000 hours per year. A total of 2900 hours are already allocated by the PAC of GANIL for the following beam time periods.

Acknowledgements:

The author would like to thank the SPIRAL staff for helping the realization of this report. The author would like to thank specially G. Auger, M. Lieuvin, E. Baron, J. Cornell, M.P. Bourgarel, Ch. Ricaud, R. Leroy, N. Lecesne, B. Jacquot and F. Chautard for the collaboration in the final version of this paper.

The SPIRAL project was funded by IN2P3-CRNS, DSM-CEA and the Lower Normandy region. It was built under the leadership of Marcel Lieuvin. A strong French and

international collaboration has been settled, being the principal actors: IPN/IN2P3 – Orsay, LPC/IN2P3 – Caen, LNS/CEA – Saclay, DAM/CEA – Bruyères-le-Chatel, CENBG/IN2P3 – gradignan, CSNSN/IN2P3 – Orsay, CIRIL – Caen, SUBATECH/IN2P3 – Nantes, Service de Prototypes/CNRS – Meudon Bellevue, CRC-IPN – Louvain-la-Neuve and ISOLDE/CERN.

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Figure Captions:

1. Diagram of the GANIL accelerators and SPIRAL.
2. Exploded view of the target-container set-up.
3. Diffusion and effusion efficiency for ^{35}Ar (T1/2 = 1.78 s) on a graphite SPIRAL target as a function of the temperature. The experimental points correspond to different microstructures (grain size) of the graphite. The continuous lines correspond to theoretical calculations using the above Arrhenius coefficients. For details, see ref. [2].
4. Charge state distribution of Nanogan-III ion source off-line, during degassing and after degassing of the target. We observe that the charge state distribution is recovered after degassing of the target.
5. Functioning diagram of CIME. The first two accelerated radioactive beams are indicated in the picture.

6. Phase measurement as a function of the radius in CIME using a 300μm silicon detector. Test realised with ^{36}Ar (ion 1) and ^{18}O (ion 2) on harmonics 3.
7. Phase distribution of the extracted ^{18}Ne beam and its main contaminant ^{18}O during the SPIRAL first experiment.
8. Preliminary results of the test reaction p(^{18}O,p)^{18}O on top and p(^{18}Ne,p)^{18}Ne on bottom. See text for details.

Table captions:

1. Average transmission from the ion source through CIME for beams included in 80πmmmrad of emittance. The number of turns is also indicated.

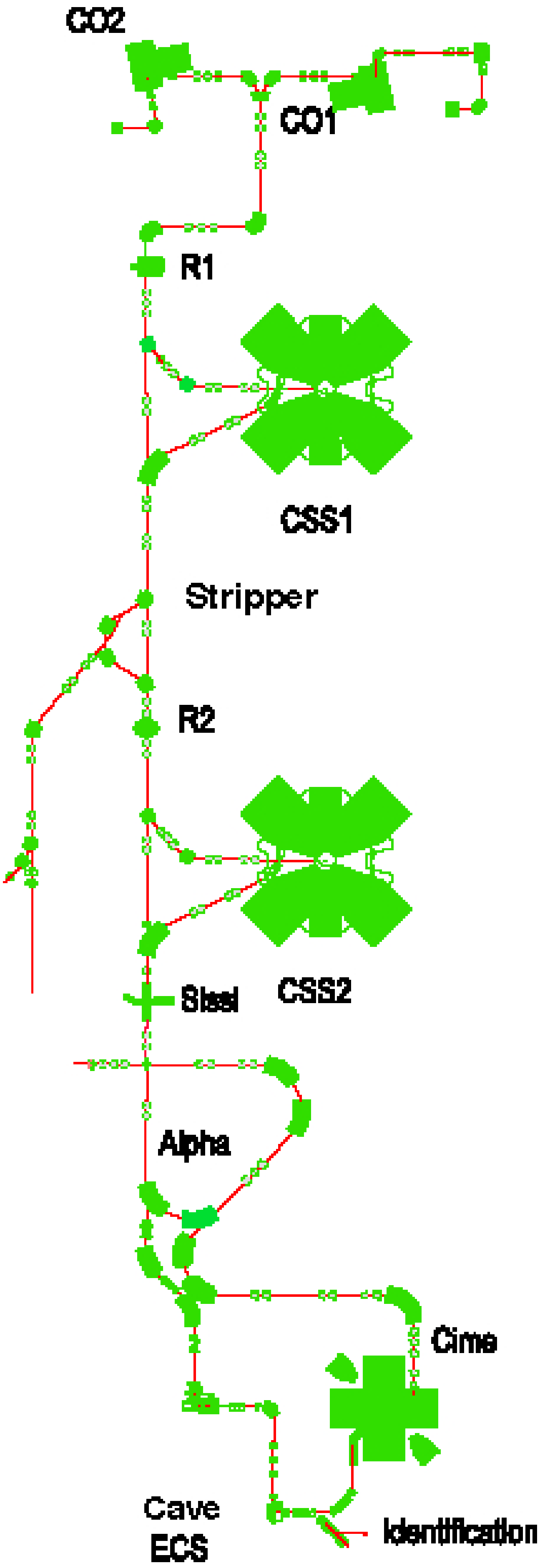

CO2
CO1
R1
CSS1
Stripper
R2
CSS2
Sissi
Alpha
Cime
Cave
ECS
Identification

Fig. 1

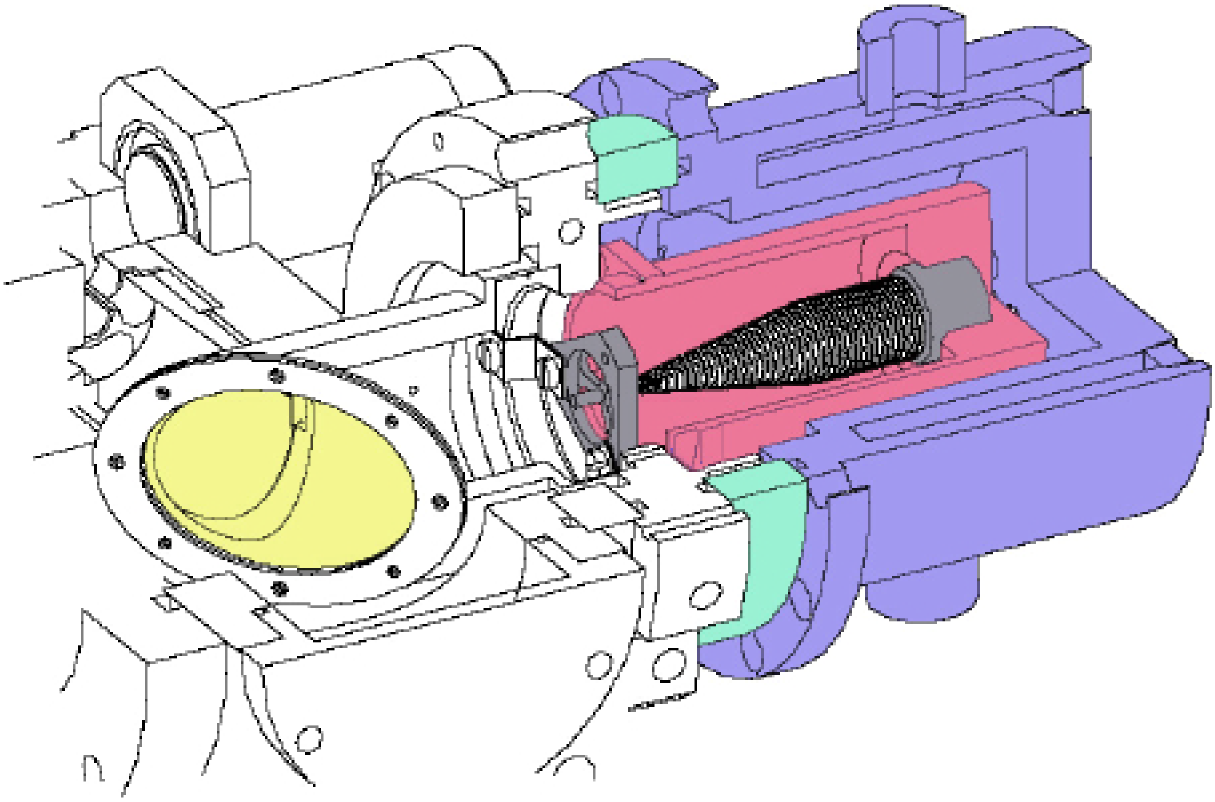
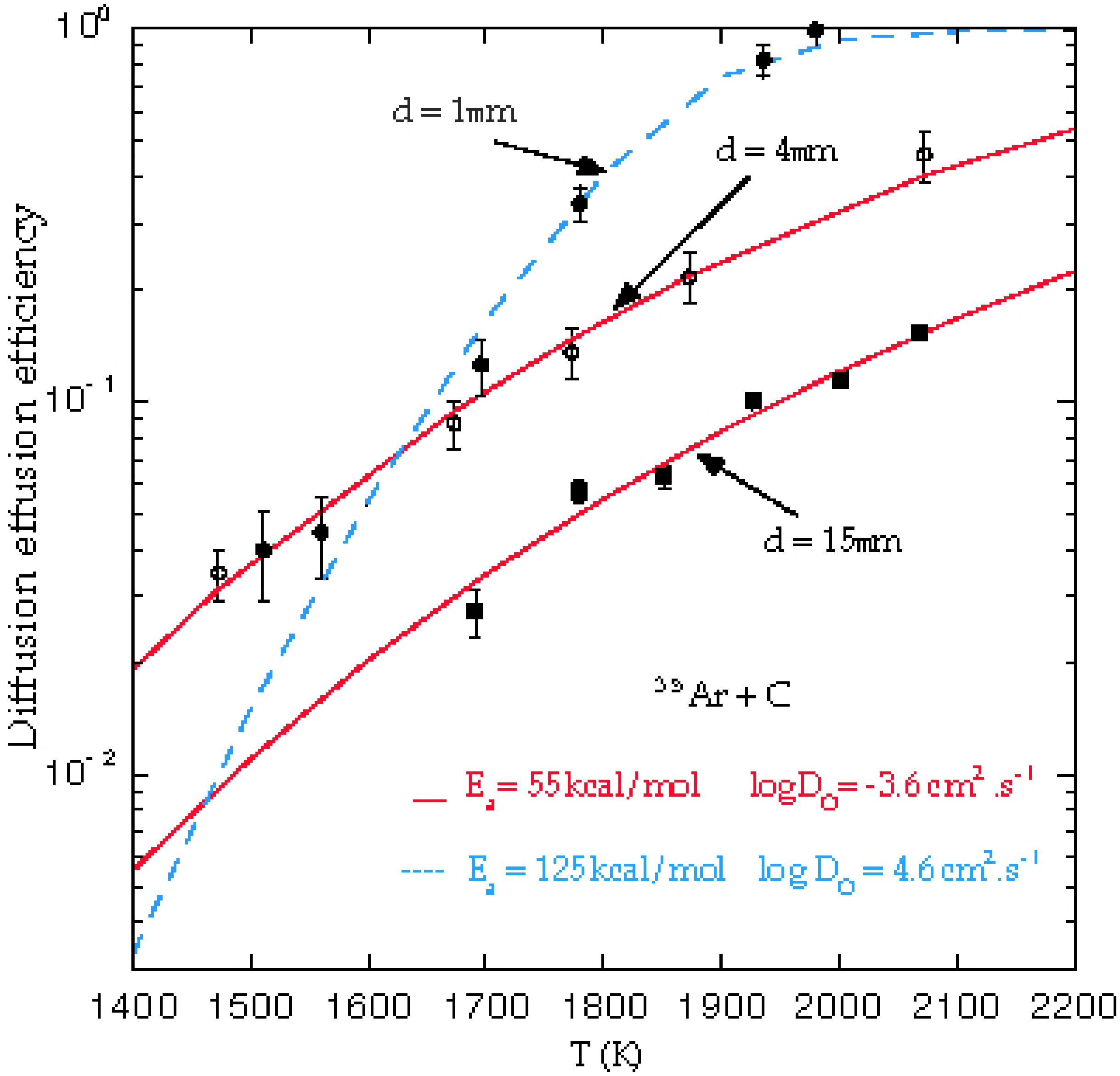
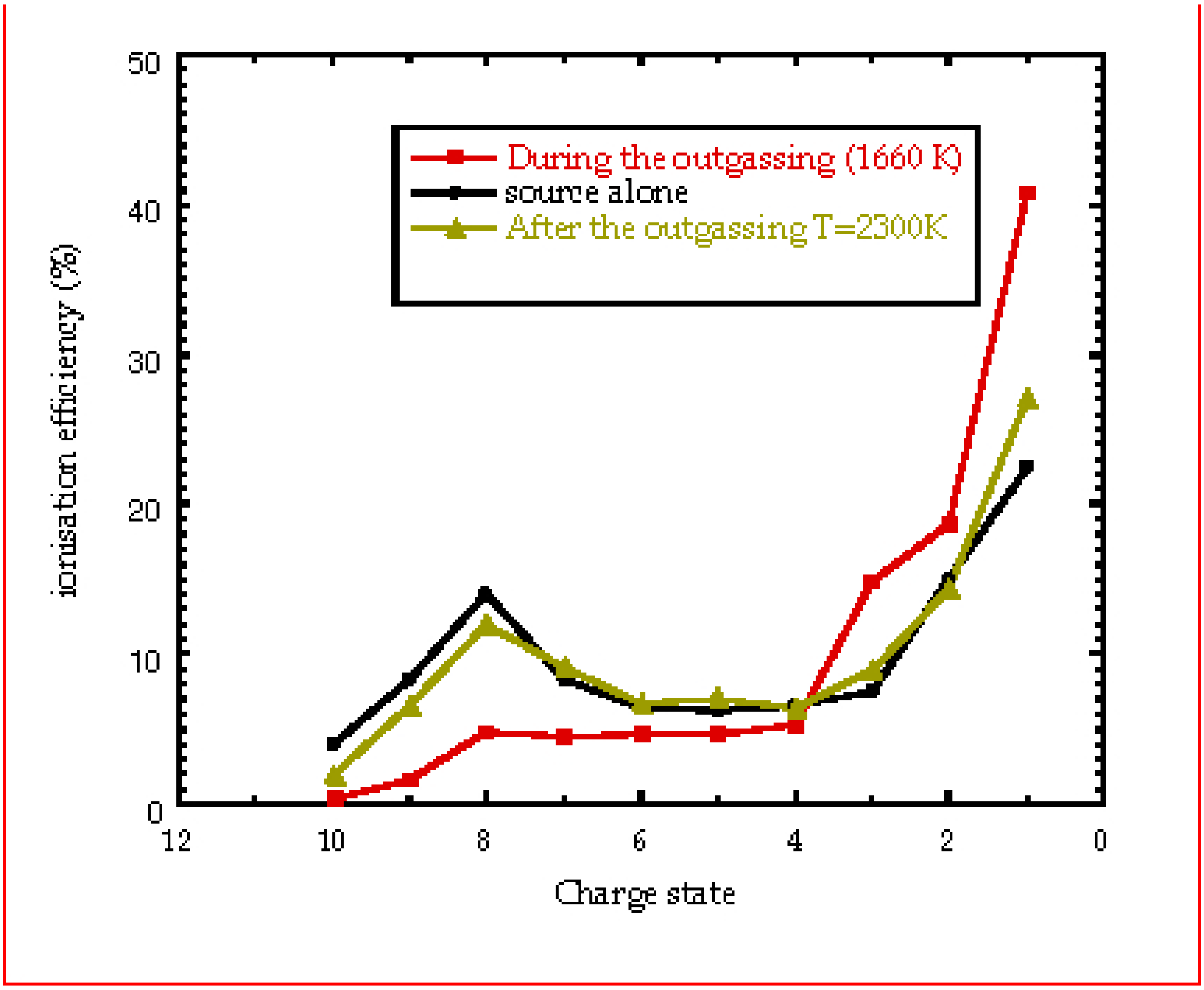


Fig. 2



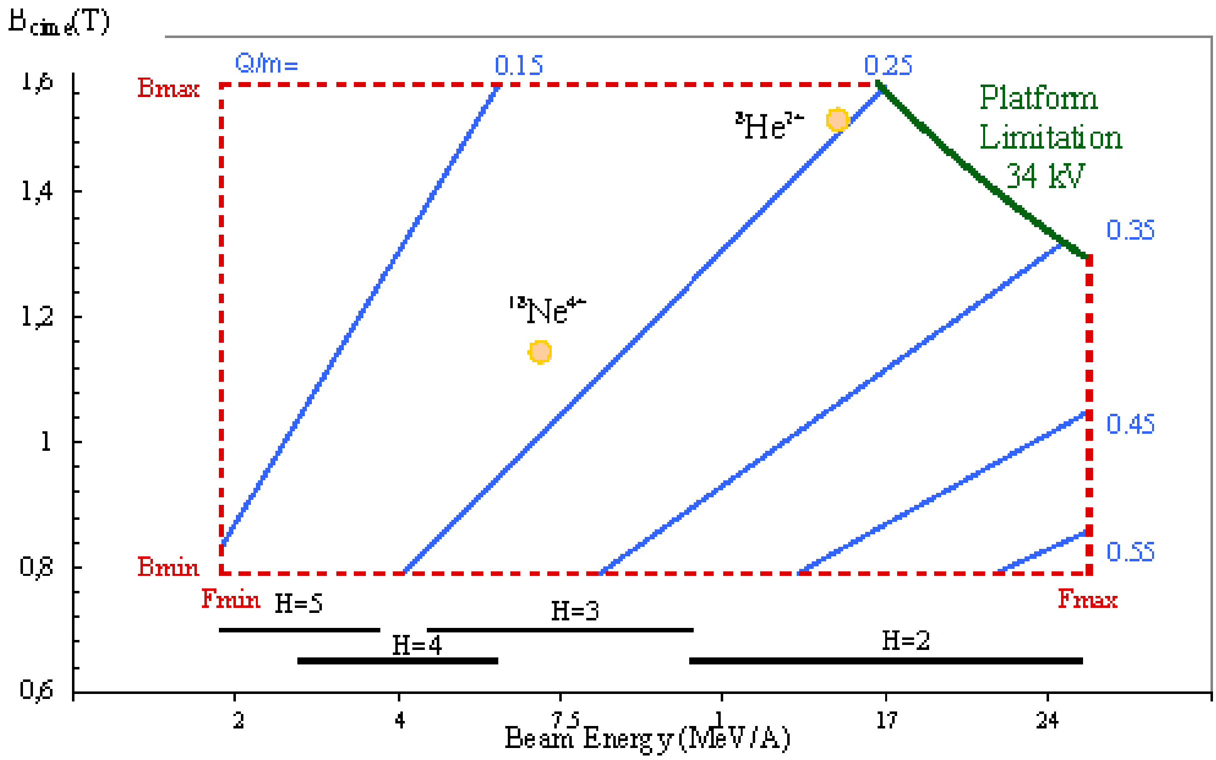
Diffusion effusion efficiency
T (K)
d = 1mm
d = 4mm
d = 15mm
^{35}Ar + C
E$_a$ = 55 kcal/mol   logD$_0$ = -3.6 cm^2.s^{-1}
E$_a$ = 125 kcal/mol   log D$_0$ = 4.6 cm^2.s^{-1}

Fig. 3



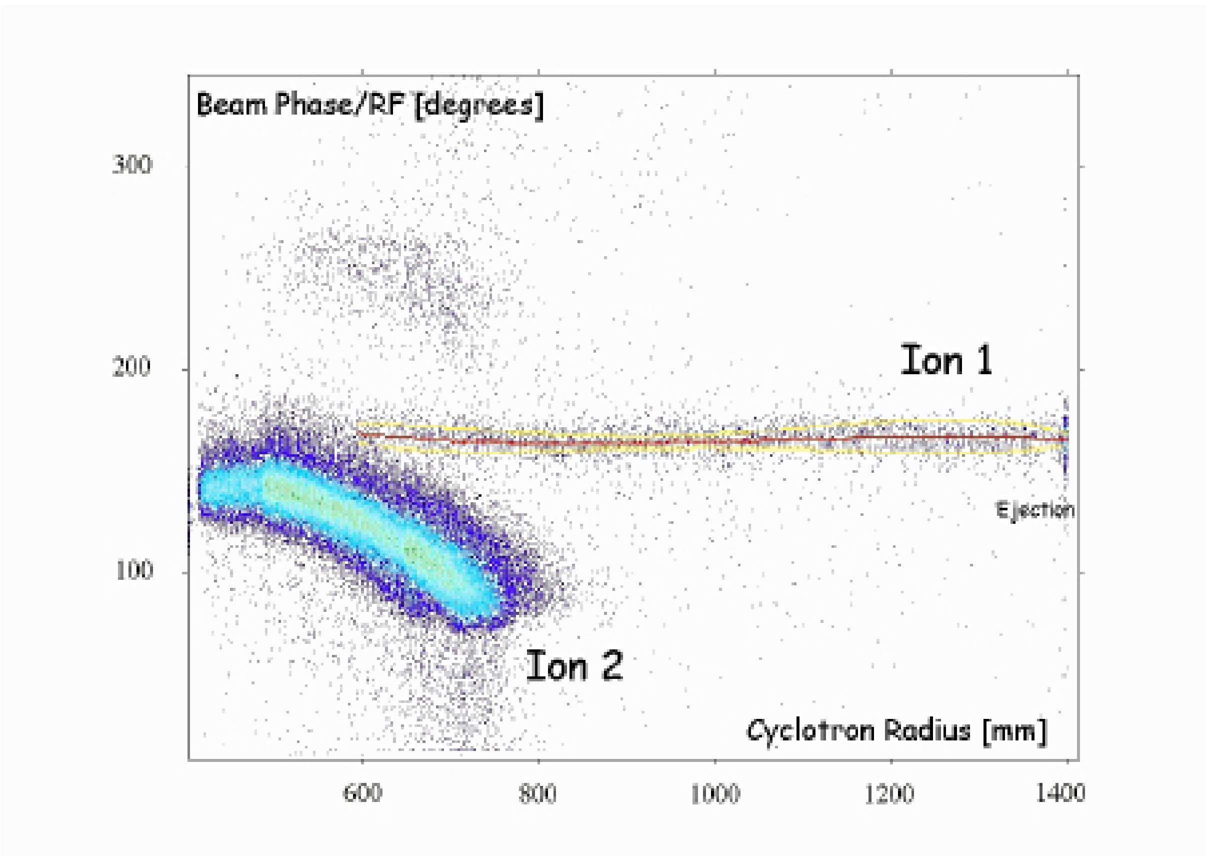
During the outgassing (1660 K)
source alone
After the outgassing T=2300K
ionisation efficiency (%)
Charge state
50
40
30
20
10
0
12
10
8
6
4
2
0

Fig. 4



B cin.(T)
Q/m=
0.15
0.25
Platform Limitation 34 kV
0.35
0.45
0.55
Bmax
Bmin
Fmin
Fmax
$^{3}He^{2+}$
$^{18}Ne^{4+}$
H=5
H=4
H=3
H=2
1,6
1,4
1,2
1
0,8
0,6
2
4
7.5
11
17
24
Beam Energy (MeV/A)

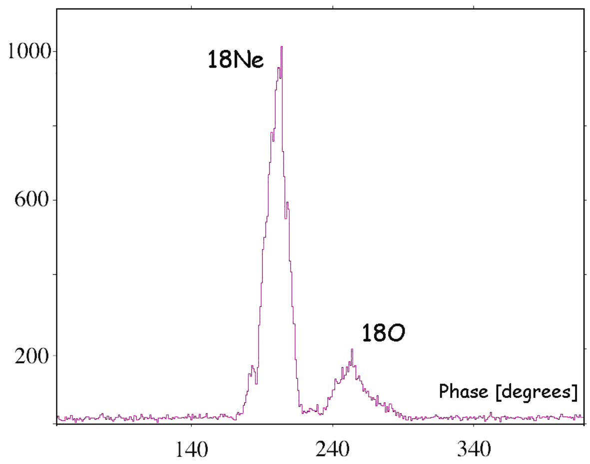
Fig. 5



Beam Phase/RF [degrees]
Ion 1
Ion 2
Ejection
Cyclotron Radius [mm]
300
200
100
600
800
1000
1200
1400

Fig. 6

Fig. 7



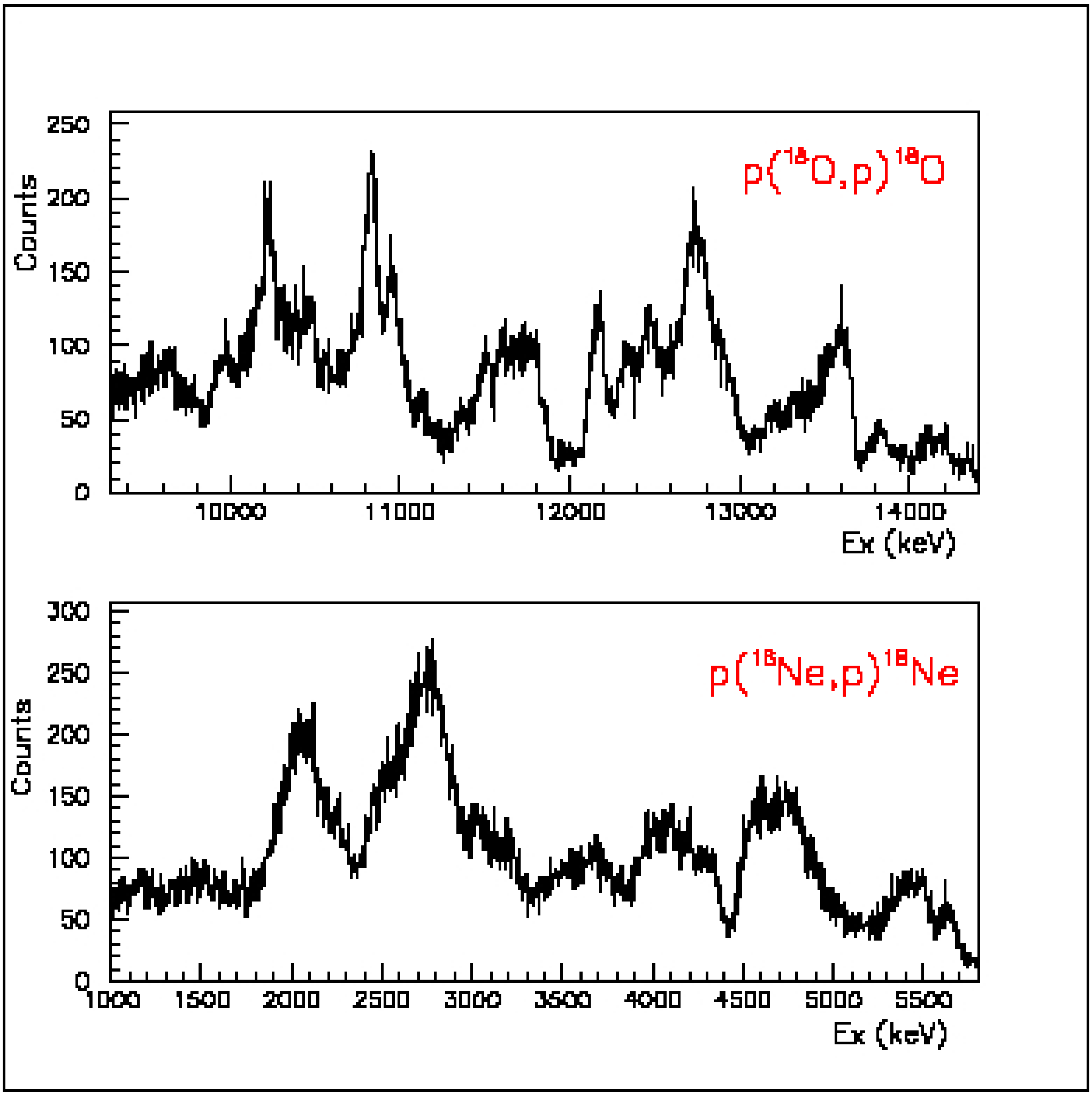


Fig. 8

Harmonic	Turn number	Transmission
2	330	~ 30%
3	280	30-40%
4	120	30-35%
5	100	15-20%

Table 1.